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STRUCTURAL EVALUATION OF TRADITIONAL TOWNHOUSE WITH TIMBER THROUGH COLUMN IN JAPAN

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ABSTRACT: This paper presents a study of the structural performance of traditional timber townhouses in a historic town in Japan. The aim of this study was to clarify the evaluation method of the structural performance of traditional timber townhouses with through column. The target area has many traditional timber townhouses built in from the late of 18th century to the early 20th century and these townhouses have few structural walls. In this study, the subjects of evaluations were typical townhouses in this area and microtremor measurement, seismic diagnosis and earthquake response analysis were performed. Results of evaluations are compared and it verifies about the difference in evaluation methods.

Key Words: Traditional timber construction, Microtremor measurement, Earthquake observation, Seismic diagnosis, Earthquake response analysis

INTRODUCTION

Japan has a long history of earthquakes. The timber structures in Japan have suffered great damage caused by strong earthquakes. Old traditional timber structures suffered especially heavy damage because many of the traditional structures often have insufficient earthquake-proof performance. Besides, many of historical towns in Japan have clear individuality of each town accordingly there are many traditional timber buildings of the same construction method or the same structural system in each area. However, the structural elements and the structural system of these towns are not often included in the structural evaluation. If the structural evaluation is suitable for the characteristics of their construction system, the technique of earthquake-proofing suitable for those buildings can be examined. Therefor it is important to clarify a suitable evaluation method in each historical area.

RESEARCH AREA

SAWARA district

The research area of the present study is the Sawara district of Chiba Prefecture, which is located near Tokyo. The Sawara district is a historical town arranged on the riverside and contains traditional timber townhouse and storehouse with thick walls as shown in figure 1. There are approximately 100 traditional buildings in the Sawara district and built in from the late of 18th century to the early 20th century (The Sawara City 2004). Many of the traditional townhouses in this area have through columns and the lattice door in the frontage of the building. The frontage direction of the first floor has

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few walls. Consequently it is expected on the timber frames with through columns for structural elements.
In the Sawara district, the research about the structural performance of the traditional townhouse was carried out from 2010 in order to become existing building safety and to build townhouses newly (Sato 2010, 2012, 2013a and 2013b). Static tests of the structural elements, analyses, microtremor measurements and an earthquake observation for the existing townhouses were performed and this paper presents a study on the existing townhouses in the Sawara district.

Figure 1. Sawara district

Previous earthquake disaster
On 11 March, 2011, timber structures suffered a great deal of damage due to the 2011 off the Pacific coast of Tohoku Earthquake. This earthquake destroyed or severely damaged 289 houses in the Katori city including the Sawara district. In the Sawara district, many falls of roofing tiles, collapse of mud walls, and foundation damage were observed as shown in figure 2.

Figure 2. Earthquake disaster observation at March 3 2011 (Townhouse C)

Subject of research
The subjects of the structural evaluation were three traditional timber townhouses as shown in table 1 and figure 3. These townhouses were built about 120 to 130 years ago (Edo era.). The target houses are building with the typical characteristics of this area. The wall quantity in the frontage direction (X) of the first floor was very few and it was not able to satisfy the current standard.

Townhouse A
This house built about 120 years ago. It is vacant dwelling now and the usage in the past was residential dwelling. Behind the building was repaired and It was excluded the repair part from subjects of this research. Because it was roofing without mud, the total weight is relatively light.
Townhouse B
This townhouse is the historical Japanese-type drapery which started in 1804. The existing building

built in 1895. It was post and beam construction and has clay tile roofing with mud. There are many through columns, but most of the size of the through columns is small. The front part of building was targeted in this study.

Townhouse C

This traditional townhouse built in 1880. The usage of this building was dwelling with bookshop and it is vacant dwelling. It suffered the damage on 11 March, 2011 and the lean-to roof was repaired after the earthquake. It was consist of post and beam as like traditional storehouse and has clay tile roofing with mud. The continuous footing of this building is constructed highly.

Table 1. Subjects of this research

	A	B	C
Photo			
Building year	about 1890	1895	1880
Area [Total]	35.1 [64.0]	47.46 [87.12]	35.5 [63.3]
Total Weight	140 kN	314 kN	309 kN
Through columns	13	18	17
Wall quantity*	0	7.66	16.48

* The frontage direction at the 1^{st} floor [cm/m^2]

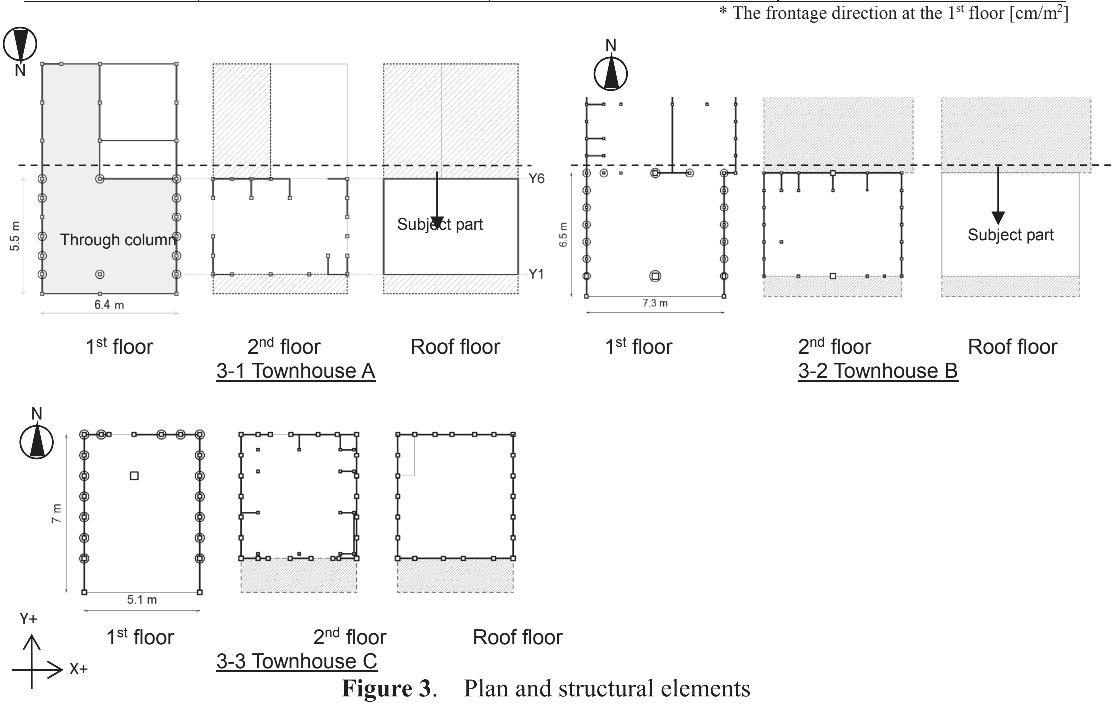


Figure 3. Plan and structural elements

VIBRATION CHARACTERISTICS

Microtremor measurement

In order to clarify and evaluate the fundamental vibration characteristics of the target townhouses, microtremor measurements (MT) and forced vibration tests (FV) were performed, as shown in table 2. Seven accelerograms were used in the tests, and they were set at the points indicated in figure 4. The natural frequency of vibration, the damping factor, and the vibration mode of the target houses were determined.

Table 2. Setting of the microtremor measurement

	MT	FV
Unit of Data	Velocity	Displacement
Sampling Frequency	200 Hz	200 Hz
Duration	5 min.	1min.
Points	60000	12000
Range	10 kine	2 mm
H.P.F.	0.1 Hz	0.1 Hz

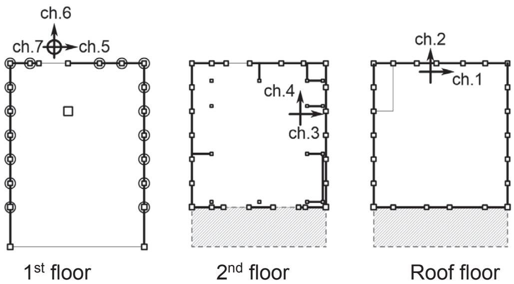


Figure 4. Plan and structural elements

Fundamental vibration characteristics

The fundamental vibration characteristics of the townhouse are shown in table 3 and the transfer functions are shown in figure 5. The natural frequency of vibration of the first mode ranged from 1.9 to 5.9 Hz. The natural frequency in the Y direction was twice as large as that in the X direction. The natural frequency of the first vibration mode was distinguished, and the natural frequency of other modes was not found in the transfer function except the townhouse C, as shown in figure 5.

The damping factor was calculated from the logarithmic decrement of the free vibration waveform. The damping factor ranged from 5% to 16%.

Table 3. Vibration characteristics

		A		B		C	
Natural Frequency (Hz)		X	Y	X	Y	X	Y
	Microtremor measurement	3.0	5.5	2.3	4.1	3.1	5.9
	Earthquake observation *	1.9	3.0	-	-	-	-
Damping Factor (%)		-	-	5	6	6	16

* Displacement became 150 times to MT

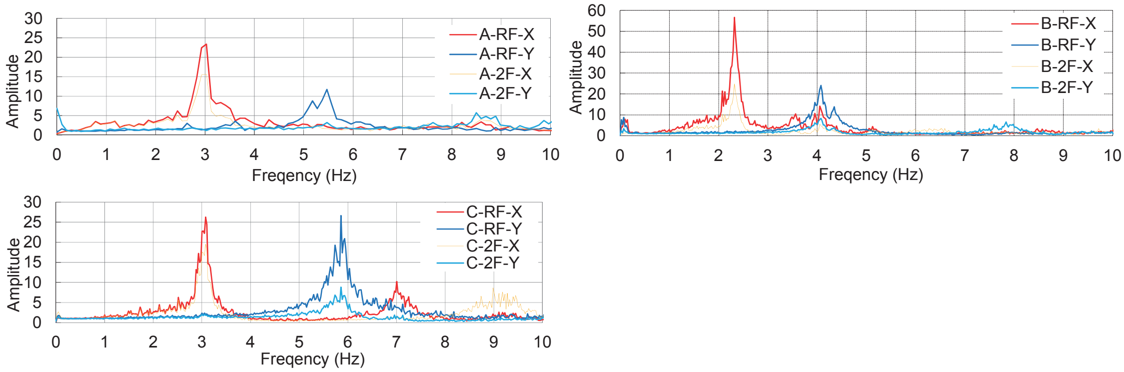


Figure 5. Transfer function

Vibration mode

The vibration modes of these houses were determined from the phase difference and the amplitude of the transfer function from MT, as shown in figure 6. The first vibration mode was observed. The displacement of the behind of the building was smaller, and the influence of the structural wall and the lean-to roof is seen.

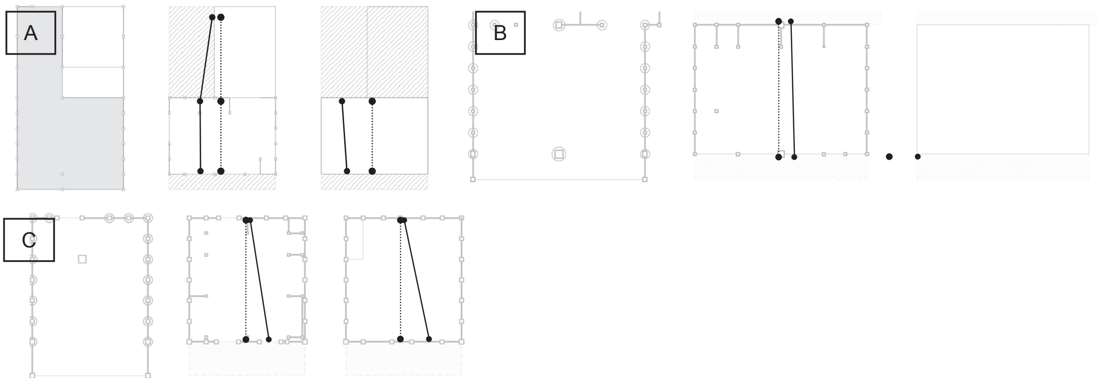


Figure 6. Vibration mode of X direction

Equivalent stiffness

The relationship between the natural frequency of vibration and the weight of traditional townhouses in this study is compared with the results of previous research (Maekawa 2000 and Inoue 1995). as shown in figure 7. The weight of all buildings compared varies from 129 to 2312 kN. The natural frequency of the X direction of the townhouses of Sawara district is higher than the overall trend. The natural frequency of the first mode of vibration is in inverse proportion to the weight of the building. The buildings are modelled as single-mass systems when applying the natural frequency and the weight of the building. The equivalent stiffness values calculated from this modelling varied from 5.2 to 42.7 kN/mm as shown in figure 8. Most of the equivalent stiffness of the X direction was 15 kN/mm and less.

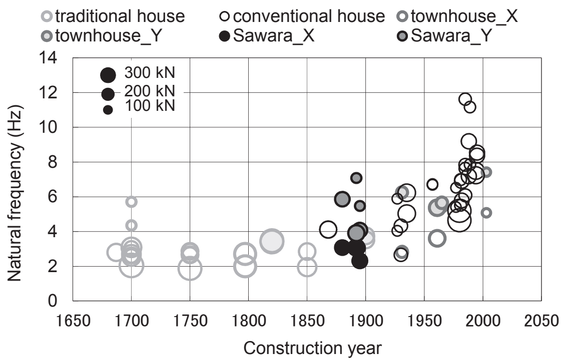


Figure 7. Natural frequency – building year

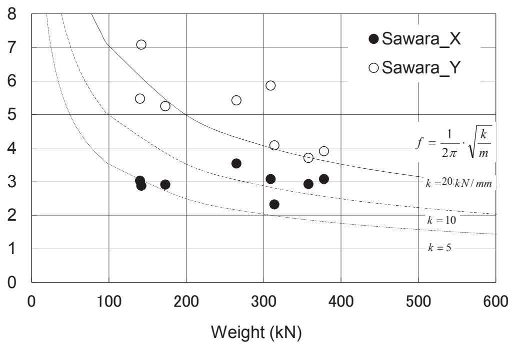


Figure 8. Natural frequency – weight

Earthquake observation

The earthquake observation was performed on the townhouse A. On 7 December 2012, the seismic intensity (JMA seismic intensity scale) observed in the Sawara district was 3.47 as shown in figure 9 (National Research Institute for Earth Science and Disaster Prevention). The maximum acceleration was approximately 42 gal recorded in this area. Five simple seismometers were set at the points shown in figure 10.

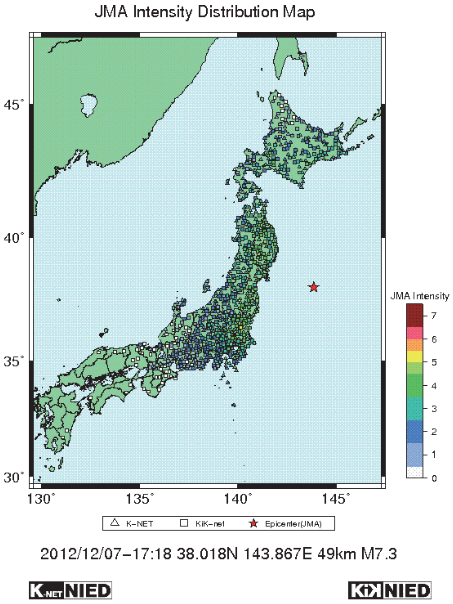


Figure 9. Seismic intensity distribution map on 7 December

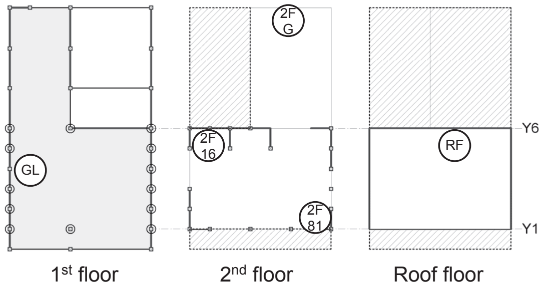


Figure 10. Measurement apparatus

Fundamental vibration characteristics

The fundamental vibration characteristics of the house were determined as shown in Table 3 above. In the earthquake observation, the amplitude became higher to 1.5 times than that of microtremor measurement, and the natural frequency of the first mode of vibration decreased to approximately 50 percent.

Load-Displacement relationship

Displacement was calculated by having integrated with the observed acceleration waveform, in consequence the load displacement relationship was presumed, as shown in figure 11. In the small earthquake, the stiffness of the X direction was small; a half of the Y direction, it was not 0.

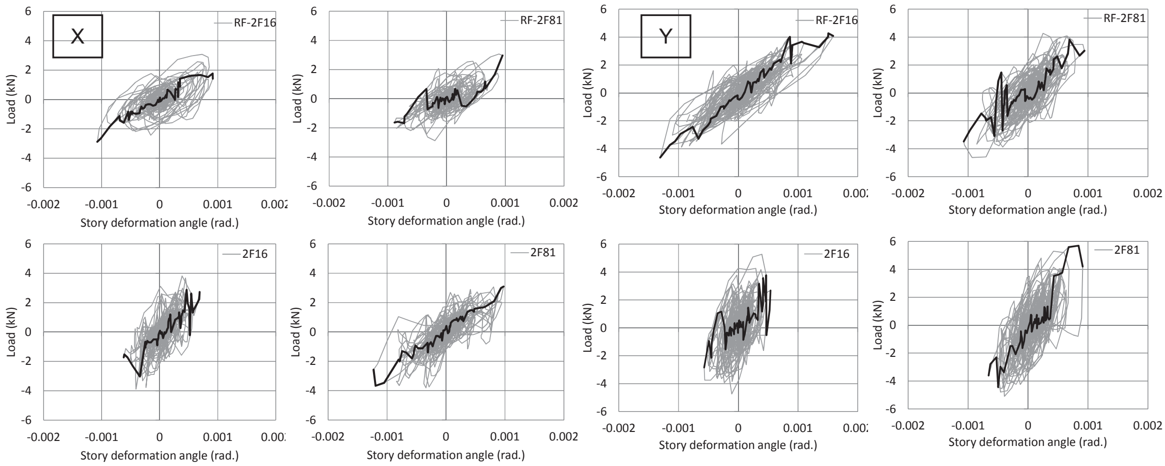


Figure 11. Load – displacement relationship (Townhouse A)

STRUCTURAL PERFORMANCE EVALUATION

Seismic diagnosis

Seismic diagnosis was performed on three timber townhouses based on the investigation (The Japan Building Disaster Prevention Association 2004). The marks of the seismic diagnoses at the first floor of the target houses varied from 0 to 0.10 in the X direction and from 0.18 to 0.51 in the Y direction. The mark calculated horizontal load-carrying capacity by necessary horizontal load-carrying capacity and if it was less than 1.0, the building have possibility of collapse. The seismic diagnosis on three townhouses in this study indicated a 'high possibility of collapse' because these townhouses on the X direction (the direction of frontage) of the first floor have few bearing walls.

Table 4. Marks of seismic diagnosis

	A	B	C
2FX	0.24	0.29	0.48
2FY	0.35	0.47	0.57
1FX	0	0.06	0.10
1FY	0.18	0.36	0.51

* based on reference [2]; 1.5～: Safe, 1.0～1.5: Temporarily Safe, 0.7～1.0: Possibility of Collapse, ～0.7: Dangerous (High possibility of Collapse)

Earthquake response analysis

The earthquake response analyses were performed on the two type analytical models of the target townhouses. The input waves were in common with each model.

Model 1: Mass system model

To evaluate the structural performance considering with through columns simplicity, the analysis was performed using the mass system model added the through columns, as shown in figure 12 and table 5. The structural elements in this analysis were mud walls at the second floor and through columns. It was determined whether the townhouse collapsed by bending strength of the through columns and relative story displacement at the first floor.

Table 5. Parameter of mass system model

	A	B	C
Structural elements	K1 = 0 (Mud walls at 1st floor) K2 = $n_w \times P$ (Mud walls at 2nd floor) $I \times n_c$ (Through columns)		
n_w	7	7.3	6.8
n_c	13	18	17
Column Section (cm)	13.5×13.5	12×12	16.5×16.5
M_{2F}	7.5 tf	15.4 tf	16.5 tf
M_{RF}	6.8 tf	13.7 tf	11.6 tf
Material	Japanese cedar fb: 70 kgf/cm^2, E: 70 tf/cm^2		

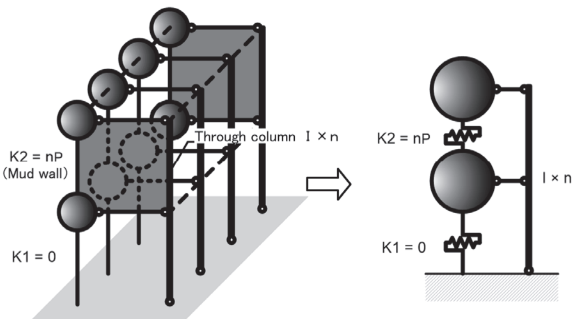


Figure 12. Mass system model

Model 2: Three-dimensional frame model

To evaluate the structural performance in detail, the townhouse A was modelled as three-dimensional frame model, as shown in figure 13. The horizontal load-resisting elements are mud walls and frames which consist of the through column and beam. The skeleton curves of the structural elements were shown in figure 14. The models of hysteresis characteristics were referenced (Architectural Institute of

Japan 2010).
Accordingly some structural elements is not clear on the investigations, the parametric study of the reduction ratio for strength due to horizontal diaphragms and beam-column joints was performed as shown table 6.

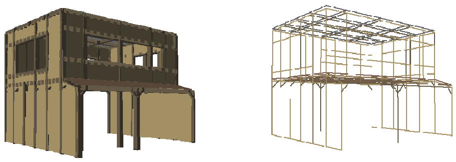
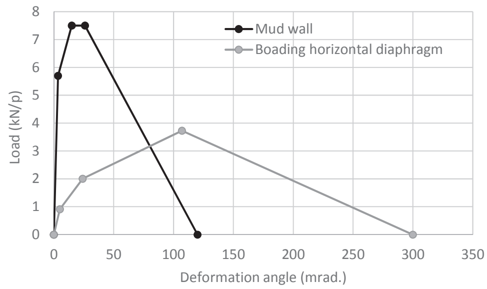


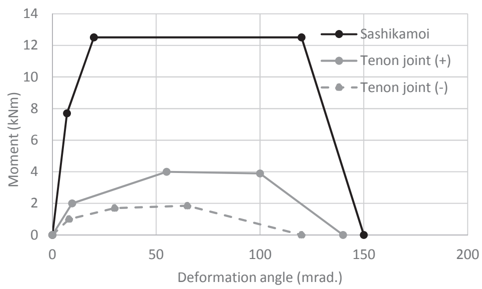
Figure 13. Analytical model (Townhouse A)

Table 6. Reduction ratio*

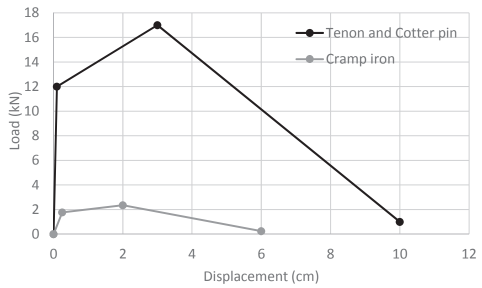
	Reduction ratio
R_{dr} (horizontal diaphragm)	1.0
	0.5
	0.1
R_{bc} (beam - column joint)	1.0
	0.5
	0.1



14-1 mud wall and floor



14-2 beam-column joint (R_{bc})



14-3 joint

Figure 14. Skelton curves of structural elements

Input wave
The input waves of the analysis were simulated earthquake motions equivalent to design earthquake ground motion based on the Japanese Code, as shown in figure 15 and 16. They were modulate to the standard level using coefficient 0.85.

Result of analysis
(1) Model 1: Mass system model
The earthquake response analyses of the mass system model were performed on the three target townhouses. As a result, the maximum story shear force varied from 36.7 to 41.3 kN. The Secant stiffness at the 1/30 radian varied from 134.8 to 356.8 kN/m, as shown in table 7 and figure 17. The structural performance of the townhouse B was smaller than other townhouses therefore it was

collapsed at all input waves because the bending strength of through columns became larger than allowable stress. The maximum story shear force and the secant stiffness of the townhouse C was the highest of the all in this study. However, at the input wave of No.1, the townhouse C was collapsed by the large deformation angle at the first floor. Meanwhile the story shear force and the stiffness of the townhouse A was smaller than that of the townhouse C, the townhouse A was not collapsed.

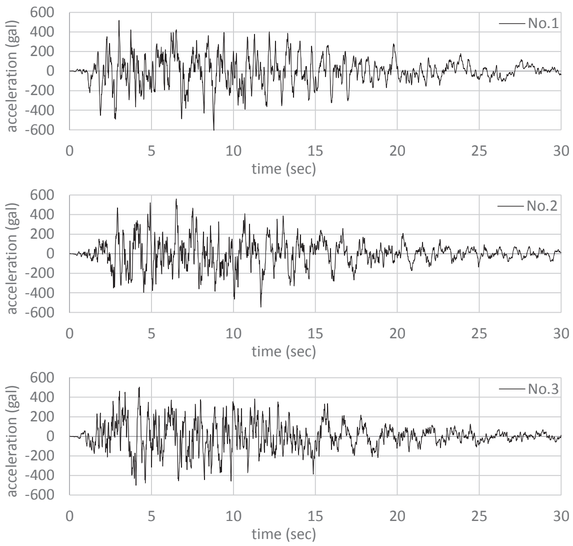


Figure 15. Time history of the input waves

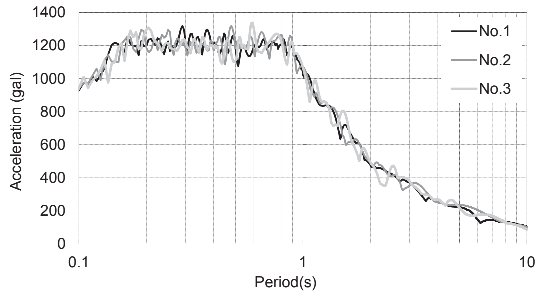
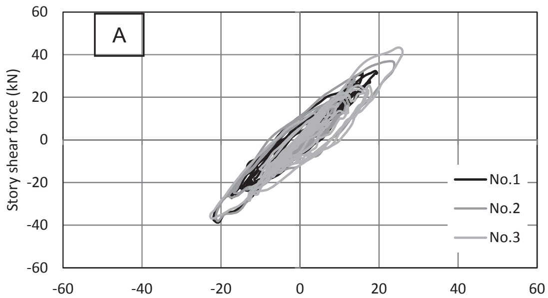
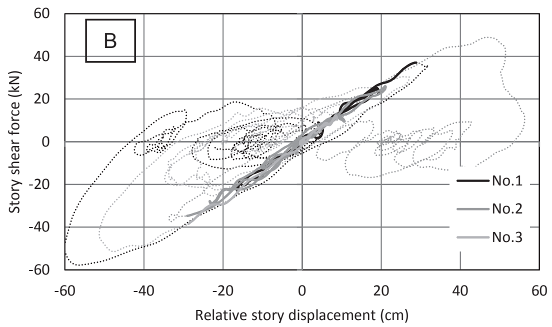


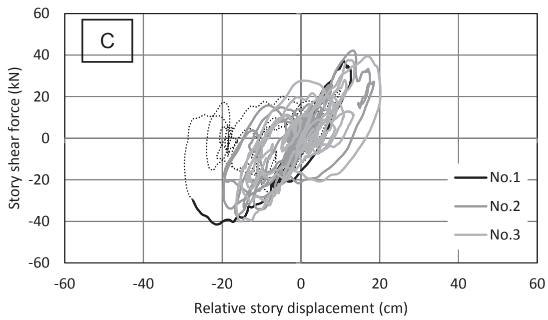
Figure 16. Acceleration response spectrum

Table 7. Result of analysis

	A	B	C
Maximum Story Shear Force	40.1 kN	36.7 kN	41.3 kN
Secant Stiffness*	212.1 kN/m	134.8 kN/m	356.8 kN/m
Collapse mode	Not collapse	Bending of through column	Large deformation angle







*bloken line: hysteresis curve after the collapse

Figure 17. Load - Displacement relationship (case 1, 1FX)

(2) Model 2: Three-dimensional frame model

The earthquake response analysis of the three-dimensional frame model was performed on the townhouse A. The load - displacement relationship on the X direction was shown in figure 18. Although the response displacement was large, it did not collapse. Therefore, the townhouse A holds the minimum earthquake-proof performance in Japan. Moreover, the differences between the displacement at the side of Y1 and Y6 were shown in figure 18, too. When the reduction ratio Rdr becomes smaller, the differences of that become larger. On the other hands, the reduction ratio Rbc did not influence on the structural performance of the townhouse A.

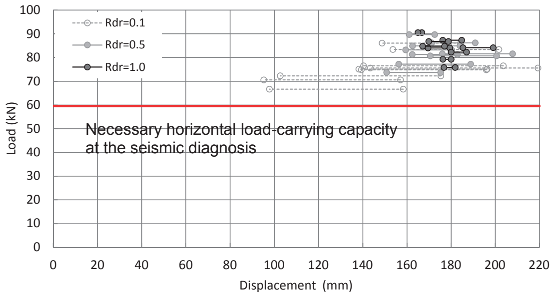


Figure 18. Load - Displacement relationship (A-1FX)

Table 8. Maximum story displacement of X direction (cm)

	Reduction ratio *								
R_{dr}	1.0			0.5			0.1		
R_{bc}	1.0	0.5	0.1	1.0	0.5	0.1	1.0	0.5	0.1
Disp.	18.2	18.0	19.2	18.4	18.0	19.1	17.0	17.7	18.0

Effect of the through column

Results of evaluations are compared and it verifies about the difference in evaluation methods. At first, on the seismic diagnosis of the current standard in Japan, it does not evaluate the structural performance of through column. Then the analysis simplicity using the mass system model can evaluate the structural performance of the townhouse in this area roughly, considering with the structural performance against the bending failure of the through columns. Moreover, the earthquake response analysis of three-dimensional frame model can evaluate the structural performance including the influence of through column in detail. The townhouse A does not have baring elements in the X direction of the first floor in the seismic diagnosis, however it was verified that the townhouse A has the minimum earthquake-proof performance in Japan on the earthquake response analysis of three-dimensional frame model. As a result, it was clarified the structural performance of the traditional townhouse with through column was influenced by the relationship between the number and size of through columns and the total weight of a building. The townhouse B has many through columns, but the column size is small and the total weights are too heavy.

Table 9. Structural performance

		A	B	C
Through columns		13	18	17
Column size (cm)		13.5	12.0	16.5
Total weight (kN)		140	314	309
C_0=	Mass model	0.29	0.12	0.13
	Frame model	0.65	-	-

CONCLUSIONS

1. In the frontage direction (X) of the first floor, the traditional townhouse in this area scarcely has structural walls nevertheless there are some earthquake-proof performances.
2. As a result of earthquake response analysis, the seismic shear coefficients were from 0.12 to 0.65. Though the earthquake-proof performance of the townhouses in this area may not be enough to the Japanese Code, it was higher than the result of the seismic diagnosis.
3. It was clarified the structural performance of the traditional townhouse in this area was influenced by the relationship between the number and size of through columns and the total weight of a building.

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